Chapter 4
GPS Reference Systems

4-1. General

In order to fully understand GPS, and its positional information, it is important to understand the reference system on which it is based. The GPS satellites are referenced to the WGS 84 ellipsoid. For surveying purposes, this earth-centered WGS 84 coordinate system must be converted (i.e., transformed) to a user-defined ellipsoid/datum, such as the Clarke 1866 (North American Datum of 1927 (NAD 27)) or Geodetic Reference System of 1980 (GRS 80) reference ellipsoids. Differential positioning provides this conversion by locating one of the receivers at a known point on the user's datum. This chapter deals with GPS reference systems and datums to which GPS coordinates can be transformed.

4-2. Geodetic Coordinate Systems

The absolute positions obtained directly from GPS pseudo-range measurements are based on the 3D, earth-centered WGS 84 ellipsoid. Coordinate outputs are on a Cartesian system (X, Y, and Z) relative to an Earth Centered Earth Fixed (ECEF) Rectangular Coordinate System having the same origin as the WGS 84 ellipsoid, i.e. geocentric. This geocentric X-Y-Z coordinate system should not be confused with the X-Y plane coordinates established on local grids; local systems usually have entirely different definitions, origins, and orientations which require certain transformations to be performed. WGS 84 Cartesian coordinates can be easily converted into WGS 84 ellipsoid coordinates (i.e., ϕ, λ, and h, geodetic latitude, longitude, and height, respectively).

4-3. WGS 84 Reference Ellipsoid

a. The origin of the WGS 84 Cartesian system is the earth's center of mass. The Z-axis is parallel to the direction of the Conventional Terrestrial Pole (CTP) for polar motion, as defined by the Bureau International Heure (BIH), and equal to the rotation axis of the WGS 84 ellipsoid. The X-axis is the intersection of the WGS 84 reference meridian plane and the CTP's equator, the reference meridian being parallel to the zero meridian defined by the BIH and equal to the X-axis of the WGS 84 ellipsoid. The Y-axis completes a right-handed, earth-centered, earth-fixed orthogonal coordinate system, measured in the plane of the CTP equator 90 deg east of the X-axis and equal to the Y-axis of the WGS 84 ellipsoid. This system is illustrated in Figure 4-1.

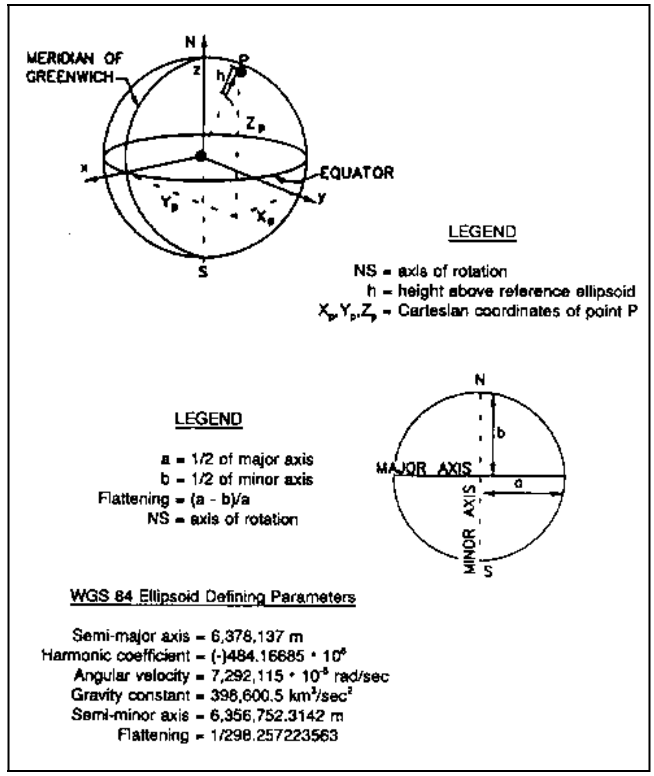

Figure 4-1. GPS WGS 84 reference ellipsoid

b. Prior to development of WGS 84, there were several reference ellipsoids and interrelated coordinate systems (datums) that were used by the surveying community. Table 4-1 lists just a few of these systems, some of which are widely used even today.

Table 4-1
Reference Ellipsoids and Related Coordinate Systems

Reference Ellipsoid	Coordinate System (Datum)
Clarke 1866	NAD 27
WGS 72	WGS 72
GRS 80	NAD 83
WGS 84	WGS 84

4-4. Horizontal Positioning Datums

One USACE application of differential GPS surveying is in densifying military construction and civil works project control. This densification is usually done relative to an existing datum (NAD 27, NAD 83, or local). Even though GPS measurements are made relative to the WGS 84 ellipsoidal coordinate system, coordinate differences (i.e., baseline vectors) on this system can, for practical engineering purposes, be used directly on any local user datum. Thus, a GPS-coordinated WGS 84 baseline can be directly used on an NAD 27, NAD 83, or even a local project datum. Minor variations between these datums will be minimal when GPS data are adjusted to fit between local datum stations. Such assumptions may not be valid when high-order NGRS network densification work is being performed.

a. North American Datum of 1927 (NAD 27). NAD 27 is a horizontal datum based on a comprehensive adjustment of a national network of traverse and triangulation stations. NAD 27 is a best fit for the continental United States. The fixed datum reference point is located at Meades Ranch, Kansas. The longitude origin of NAD 27 is the Greenwich Meridian with a south azimuth orientation. The original network adjustment used 25,000 stations. The relative precision between initial point monuments of NAD 27 is by definition 1:100,000, but coordinates on any given monument in the network contain errors of varying degrees. As a result, relative accuracy between points on NAD 27 may be far less than the nominal 1:100,000. The reference units for NAD 27 are U.S. Survey Feet.

b. North American Datum of 1983 (NAD 83). NAD 83 uses many more stations and observations than NAD 27, including some satellite-derived coordinates, to readjust the national network (a total of approximately 250,000 stations were used). The longitude origin of NAD 83 is the Greenwich Meridian with a north azimuth orientation. NAD 83 has an average precision of 1:300,000. NAD 83 is based upon the GRS 80, an earth-centered reference ellipsoid, and for most practical purposes is equivalent to WGS 84, which is currently the best available geodetic model of the shape of the earth surface worldwide. The reference units for NAD 83 are meters.

c. HARNs Network Survey Datum. The nationwide horizontal reference network was redefined in 1983 and readjusted in 1986 by the NGS. It is known as the North American Datum of 1983, adjustment of 1986, and is referred to as NAD 83 (86). It is accurate to 1 part in 100,000 which normally satisfies USACE surveying, mapping, and related spatial database requirements. USACE adopted this datum on 5 March 1990. Since that time, several states and the NGS have begun developing High Accuracy Reference Networks (HARNs) for surveying, mapping, and related spatial database projects. These networks, developed exclusively with GPS, are accurate to 1 part in 1,000,000. HARNs have a slightly different coordinate, usually within one meter of those in NAD 83 (86), resulting in two coordinate values for the same survey point. Since the confusion and potential litigation inherent with multiple coordinates with the same point can adversely impact design, construction, boundary location, and other functions, use of HARNS is not recommended.

d. Geodetic survey datums. GPS uses the WGS 84 reference ellipsoid for geodetic survey purposes. GPS routinely provides differential horizontal positional results on the order of 1 ppm, compared to the accepted results of 1:300,000 for NAD 83 and (approximately) 1:100,000 for NAD 27. Even though GPS has such a high degree of precision, it provides only coordinate differences; therefore, ties to the national network to obtain coordinates of all GPS stations must be done without distorting the established control network (i.e., degrade the GPS-derived vectors during the adjustment). Generally, on midsize survey projects, three or more horizontal control stations from the national network can be used during the GPS observation scheme. In order to facilitate a tie between GPS and existing networks for horizontal control, an adjustment of the whole network scheme (all control and GPS-derived points) should be completed. There are many commercial software packages that can be used to perform this adjustment. Once a network adjustment meets the accuracy requirement, those values should not be readjusted with additional points or observations.

e. Local project datums. Several projects can be based on local project datums. These local datums might be accurate within a small area, but can become distorted over larger areas. Most local project datums are not connected to any other datums, but can be tied to outside control and related and transformed to another datum. It is important to understand how this local datum was established in order to relate it or perform a transformation to some other datum.

f. State Plane Coordinate System. The SPCS was developed by the NGS to provide a planar representation of the earth's surface. To properly relate spherical coordinates (ϕ,λ) to a planar system (Northings and Eastings), a developable surface must be constructed. A developable surface is defined as a surface that can be expanded without stretching or tearing. The two most common developable surfaces or map projections used in surveying and mapping are the cone and cylinder. The projection of choice is dependent on the north-south or east-west extent of the region. Areas with limited east-west dimensions and elongated north-south extent utilize the Transverse Mercator projection. Areas with limited north-south dimensions and elongated east-west extent utilize the

Lambert projection. For further information on the State Plane Coordinate System see EM 1110-1-1004.

4-5. Orthometric Elevations

Orthometric elevations are those corresponding to the earth's irregular geoidal surface. Measured differences in elevation from spirit leveling are generally relative to geoidal heights--a spirit level bubble (or pendulum) positions the instrument normal to the direction of gravity, and thus parallel with the local slope of the geoid. Elevation differences between two points are orthometric differences, a distinction particularly important in river/channel hydraulics. Orthometric heights for the continental United States (CONUS) are generally referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88); however, other vertical datums may be used in some projects (e.g., the International Great Lakes Datum of 1955 (IGLD 55) or International Great Lakes Datum of 1985 (IGLD 85)), which is a dynamic/hydraulic-based datum, not an orthometric datum).

4-6. GPS WGS 84 Ellipsoidal Heights

GPS-determined heights or height differences are referenced to an idealized mathematical ellipsoid, i.e., WGS 84. This WGS 84 ellipsoid differs significantly from the geoid; thus, GPS heights are not the same as the orthometric heights which are needed for standard USACE projects (i.e. local engineering, construction, and hydraulic measurement functions). (See Figure 4-2.) Accordingly, any WGS-84-referenced height obtained using GPS must be transformed to the local orthometric vertical datum. This requires adjusting and interpolating GPS-derived heights relative to fixed orthometric elevations. Such a process may or may not be of suitable accuracy (i.e. reliability) for some engineering and construction work. See Table 6-1 in Chapter 6.

4-7. Orthometric-WGS 84 Elevation Relationship

The relationship between a WGS 84 ellipsoidal height and an orthometric height relative to the geoid can be obtained from the following equation:

$$h = H + N \tag{4-1}$$

where

h = ellipsoidal height

H = elevation (orthometric)

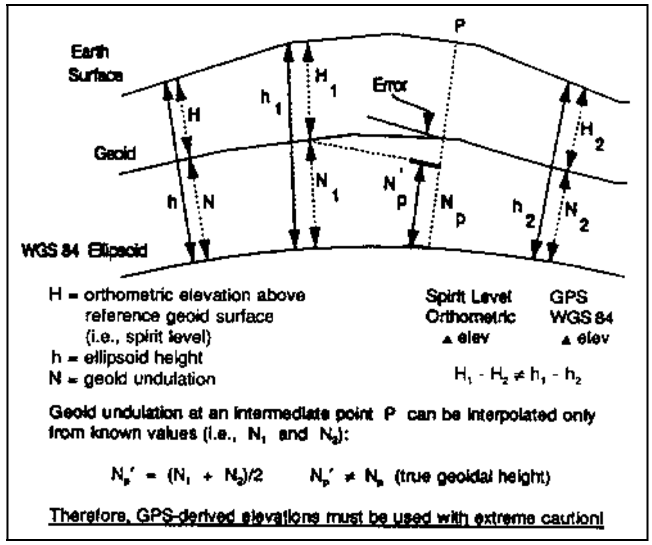

Figure 4-2. GPS ellipsoid heights

N = geoid undulation

a. Due to significant variations in the geoid, even over small distances, elevation differences obtained by GPS cannot be directly equated to orthometric (or spirit level) differences. Geoid modeling techniques are often used to obtain the parameter N in Equation 4-1; however, accuracies may not be adequate for engineering purposes. Some small project areas where the geoid stays fairly constant or local geoid modeling can be performed, elevation differences obtained by GPS can be used. See Chapter 6 for further information on the concept of vertical densification with GPS.

b. GPS surveys can be designed to provide elevations of points on the local vertical datum. This requires connecting to a sufficient number of existing orthometric benchmarks from which the elevations of unknown points can be "best fit" by some adjustment method--usually a least squares minimization. This is essentially an interpolation process and assumes linearity in the geoid slope between two established benchmarks. If the geoid variation is not linear, then the adjusted (interpolated) elevation of an intermediate point will be in error. Depending on the station spacing, location, local geoid undulations, and numerous other factors, the resultant interpolated/adjusted elevation accuracy is usually not suitable for construction surveying purposes; however, GPS-derived elevations may be adequate for small-scale topographic mapping control.